

Effect of a Starch-Lipid Fat Replacer on the Rheology of Soft-Serve Ice Cream

J. BYARS

ABSTRACT: The rheology of soft-serve ice creams prepared with Fantesk™, a starch-lipid composite, was compared to a commercial product. Fantesk™ describes a class of stable starch-lipid composites formed by steam-jet cooking, and is used in this case as a fat replacer. Waxy maize starch and butter were used, and the butter content was selected to give 0.5 to 1.1 wt% butter in the ice cream mix. Despite the lower level of fat, the overrun and rheological properties of the Fantesk™-based ice creams were similar to the commercial product when differences in the freezing behavior of the different formulations were accounted for.

Keywords: ice cream, rheology, soft-serve, Fantesk™

Introduction

ICE CREAM IS A COMPLEX FOOD FOAM SYSTEM CONSISTING OF air, fat, ice, and serum phases. Each of these phases affects the overall texture and quality of the final product. Rheology has proven to be useful for measuring the physical properties of ice cream, and for determining the effects of changes in composition. Sherman (1965, 1966) and Shama and Sherman (1966) modeled the creep behavior of ice cream and ice cream mix, and related changes in rheology to composition, temperature, and overrun. These researchers used a 6-element spring-and-dashpot model to determine the effect of each component on the overall structure. Dea and others (1984) measured the linear viscoelasticity of ice cream as a function of temperature. The temperature dependence of the storage modulus was used to relate its value to the volume fraction of ice. Goff and others (1995) investigated the effects of temperature, polysaccharide stabilizers, and overrun on the linear viscoelasticity of ice cream and ice cream mix. Their results showed that air bubbles and polysaccharide stabilizers also affected the storage modulus. Addition of polysaccharide increased the mix viscosity, while decreasing the storage and loss moduli and $\tan \delta$. The influence of protein- and carbohydrate-based fat replacers on the linear viscoelasticity of ice cream was studied recently by Adapa and others (2000). They found that the fat replacers increased the viscous properties, but had little effect on the elastic properties. Much less attention has been given to the rheology of soft-serve ice cream. Goyal and others (1973) showed that the viscosity of soft-serve mixes increased slightly when glycerol monostearate, corn syrup, or dextrose was added, but no reports of the rheology of frozen soft-serve ice cream are available.

This work considers the rheology of both a commercial low-fat soft-serve ice cream and a series of soft-serve ice creams prepared with Fantesk™ (USDA). Fantesk™ is a stable starch-lipid composite prepared by co-jet cooking starch, lipid, and water with excess steam (Fanta and Eskins 1995; U.S. Patent 5,882,713). The result is a stable dispersion of 1 to 10- μ m oil droplets encapsulated in a starch matrix. Composites can be prepared with up to 50% lipid by weight. The cooked product can be drum-dried and easily re-

dispersed in water. Fantesk™ has previously been used to prepare reduced-fat cookies, cheese, and meat products (Brandt 2000).

The objective of this work was to compare the properties of a commercial soft-serve ice cream with those of reduced-fat soft-serve ice creams prepared with Fantesk™. The effects of Fantesk™ composition and concentration on the mix, the ice cream freezing and melting behavior, and the mix and ice cream rheology were studied.

Materials and Methods

Fantesk™ preparation

The Fantesk™ composite was prepared according to the procedure discussed by Fanta and Eskins (1995). Waxy maize starch (Staley, Decatur, Ill., U.S.A.) was suspended in distilled water at 15% dry weight basis with a Waring® (East Windsor, N.J., U.S.A.) blender. This slurry was passed through a jet cooker at 17 ml/s and combined with excess steam. The steam inlet pressure was 640 kPa, and the backpressure was 380 kPa. The cooked product was collected, blended with melted butter (Grade AA unsalted butter, 80% butterfat, Prairie Farms, Carlinville, Ill., U.S.A.), and then cooked again under the same conditions. The cooked starch was much more viscous than water, so blending the butter into previously cooked starch kept the butter dispersed until it passed through the jet cooker, thus assuring a more uniform final product. After the second cook, each product was drum-dried at 520 kPa steam pressure. The dried product was then milled (Fritsch Laboratory Cutting Mill, Idar-Oberstein, Germany) to pass through a 4-mm mesh.

Ice cream mix

Fantesk™-based soft-serve mixes were prepared with different levels of Fantesk™, and with Fantesk™ having different butter:starch ratios. The compositions of each mix and its fat content are shown in Table 1. The composition of the mixes was selected to yield an acceptable frozen product without any obvious sensory defects, rather than to duplicate the rheology of the commercial product. The level and composition of Fantesk™ was varied within the range that gave acceptable products. The mixes denoted as 3%, 4%, and 5% Fantesk™ used an identical butter:starch ratio of 2:5,

Table 1—Composition of ice cream mixes with ingredient amounts in weight percent

	3% Fantesk™	4% Fantesk™	5% Fantesk™	3.4% Fantesk™	Commercial
butter:starch	2:5	2:5	2:5	1:5	
skim milk	75.9	75.1	74.3	75.6	
NFDM	3.9	3.9	3.9	3.9	
corn syrup	11.1	11.0	10.9	11.1	
Sucrose	6.1	6.0	6.0	6.0	
% fat in mix	0.7	0.9	1.1	0.5	3.5
wt% solids	30.3	30.0	31.2	29.9	31.1
density [kg/m ³]	1116	1120	1122	1118	1101

Table 2—Properties of frozen soft-serve ice cream

	% overrun	T _{transition} [°C]	T _{measurement} [°C]	T _{melting} [°C]	melt rate [g/100g/min]
3% Fantesk™	48.9 ± 3.1	-6.4 ± 0.3	-4.7	-4.0 ± 0.7	2.55
4% Fantesk™	49.4 ± 2.5	-5.7 ± 0.3	-4.0	-3.0 ± 0.7	2.44
5% Fantesk™	46.9 ± 1.6	-5.7 ± 0.3	-4.0	-3.0 ± 0.7	2.67
3.4% Fantesk™	49.8 ± 3.0	-5.7 ± 0.3	-4.0	-3.0 ± 0.7	2.50
Commercial	51.5 ± 3.5	-7.3 ± 0.3	-5.6	-4.7 ± 0.7	2.34

whereas the Fantesk™ in the mix denoted “3.4% Fantesk™” used about half as much butter. The amount of starch present in the mix was the same for the 3.4% and 4% Fantesk™ mixes. In each case, the milled Fantesk™ was added to the skim milk while heating and stirring, which readily dispersed the Fantesk™. The non-fat dry milk solids (Carnation instant nonfat dry milk, Nestlé USA, Solon, Ohio, U.S.A.), corn syrup (Karo light corn syrup, Best Foods, Englewood Cliffs, N.J., U.S.A.), and sucrose were then added as the temperature was brought to 80 °C, where it was held for 15 min. The mix was then transferred to a plastic bag and quenched in an ice bath. The cooled mix was then stored at 4 °C overnight. The commercial soft-serve mix (Prairie Farms, Carlinville, Ill., U.S.A.) contained 3.5% fat and was used as received. The density of each mix was measured in a calibrated pycnometer at 25 °C, and the total-solids concentration was measured by freeze-drying.

Ice cream preparation

Ice creams were prepared in an Electro-Freezer® CS2 soft-serve gravity-fed freezer (East Moline, Ill., U.S.A.). As discussed below, the draw temperature for each soft-serve was based on its freezing properties. The draw temperature could not be controlled precisely, but was always within 0.5 °C of the measurement temperature for each soft-serve. To prevent melting before the rheological measurements could be conducted, samples were collected in a Dewar flask. The mix feed assembly, which controls the amount of air incorporated into the final product, was maintained in the same position for all tests. The overrun for each sample is given in Table 2. Measurements of the overrun at a given time were reproducible within 1% overrun, so the standard deviation given in Table 2 indicates a variation in overrun during a set of experiments. The differences in overrun between samples were not statistically significant. No differences in the rheological properties of the soft-serve ice creams were observed for changes of the overrun in this range. Table 2 indicates that, despite the lower fat level in the Fantesk™ and the fact that the fat was in a starch composite, an overrun of nearly 50% was still obtained.

Rheological measurements

The viscosities of the ice cream mixes were measured on a Rheometrics® ARES controlled-strain fluids rheometer (Rheometric Scientific, Piscataway, N.J., U.S.A.), using a 50-mm diameter, 0.04 radian cone. A circulating water bath was used to maintain the temperature of the bottom plate at 6.0 ± 0.1 °C. Measurements on the prepared ice cream were conducted on a Rheometrics® ARES controlled-strain melts rheometer with 25-mm dia serrated parallel plates. The rheometer was equipped with an air convection oven and a mechanical chiller to allow temperature control within ± 0.1 °C. The measurement temperature for each ice cream is given in Table 2, and the method for determining this temperature is discussed below. Reported results are mean values of at least 2 measurements, and a fresh sample was used for each measurement. Repeated measurements were typically within 10% of each other, but some varied by as much as 20%. Stress relaxation experiments at large strain were especially difficult to reproduce exactly. Data were analyzed by analysis of variance, and significance of differences was defined at $p \leq 0.05$. Fits of the linear viscoelastic spectra were obtained using a Levenberg-Marquardt algorithm with MathCad™ software (MathSoft, Cambridge, Mass., U.S.A.). Integrations of the K-BKZ equation were also performed with MathCad. The intrinsic viscosity of the jet-cooked starch was measured using a Schott AVS 360 automated viscosity system (Hofheim, Germany).

Results and Discussion

RHEOLOGICAL RESULTS ARE PRESENTED FOR 5 DIFFERENT soft-serve ice creams: a commercial product and 4 different Fantesk™-based mixes. The Fantesk™ concentration and composition were selected in the range that gave acceptable products. Three different starch levels and 4 different fat levels were studied.

The viscosities of the mixes at 6 °C are shown in Figure 1 for each mix. No slip was observed for any of the mixes. Upon startup of a steady shear flow, the viscosity of each mix increased to a steady value, with an overshoot at higher rates. The viscosity of the 3% Fantesk™ mix approaches a constant value at low shear rates, but each of the other mixes is shear-thinning across the entire range of shear rates mea-

Table 4—Zero-shear-rate viscosity and Maxwell relaxation time from linear viscoelastic spectrum, and the predictions of the K-BKZ model for the viscosity and relaxation time at a shear rate of 1 s⁻¹

	η_0 [10 ⁵ Pa·s]	λ_0 [s]	$\eta(\dot{\gamma} = 1 \text{ s}^{-1})$ [Pa·s]	$\lambda(\dot{\gamma} = 1 \text{ s}^{-1})$ [s]
3% Fantesk™	7.8	77	1220	0.019
4% Fantesk™	7.6	75	2110	0.018
5% Fantesk™	7.7	77	1600	0.018
3.4% Fantesk™	7.7	80	1440	0.017
Commercial	5.6	88	1350	0.022

Table 3—Damping function coefficients from stress relaxation experiments

	K	a ₁	a ₂
3% Fantesk™	0.93	0.61	0.056
4% Fantesk™	0.97	0.42	0.040
5% Fantesk™	0.97	0.39	0.034
3.4% Fantesk™	0.96	0.49	0.046
Commercial	0.92	0.64	0.049

sured, and no zero-shear-rate viscosity could be obtained for the sensitivity of this rheometer. The 5% Fantesk™ mix had the highest viscosity, and its viscosity was on average 1.8 times higher than for the 3.4% mix. The 3.4% and 4% mixes had the same total starch content, but they had slightly different viscosities at low shear rates. This is most likely due to batch-to-batch variations in the degradation of the starch in the jet cooker. The Fantesk™ used for the 3%, 4%, and 5% mixes all came from the same batch. The viscosity of the commercial mix decreases more sharply with shear rate than the Fantesk™-based mixes, so although its viscosity is about 1.4 times higher than the viscosity of the 3.4% Fantesk™ mix at the lowest rates, it is only 0.6 times as high at high shear rates. The increase in viscosity with starch content is not surprising, considering the high molecular weight of the starch in the Fantesk™. Even after passing through the jet cooker twice, waxy maize starch has an intrinsic viscosity of 115 ml/

g in 90/10 dimethyl sulfoxide/water, which corresponds to a molecular weight of 8 × 10⁷ g/mol (Millard and others 1997). However, amylopectin is highly branched and water is a poor solvent for amylopectin, so the effect of the addition of high molecular weight amylopectin on the solution viscosity is not as great as for fully expanded random coil molecules. The changes in viscosity of the Fantesk™-based mixes had no observable effect on the operation of the soft-serve machine.

Changes in the mix composition will also affect the freezing behavior of the final product, and these changes must be taken into account in order to compare samples under similar conditions. Ideally, the ice phase fraction would be held constant, but this could not be measured directly. Measurements of the freezing point depression for each mix would give an indication of different freezing behavior, but would not relate directly to the ice fraction of the ice cream below its freezing point. A more complete understanding of the temperature dependence of the soft-serve ice creams can be obtained by measuring the complex viscosity, η^* , as a function of temperature, as shown in Figure 2. A sample was placed in the rheometer and equilibrated to an initial temperature between -10 °C and -12 °C. The complex viscosity at a frequency of 1 rad/s was measured, and then the tem-

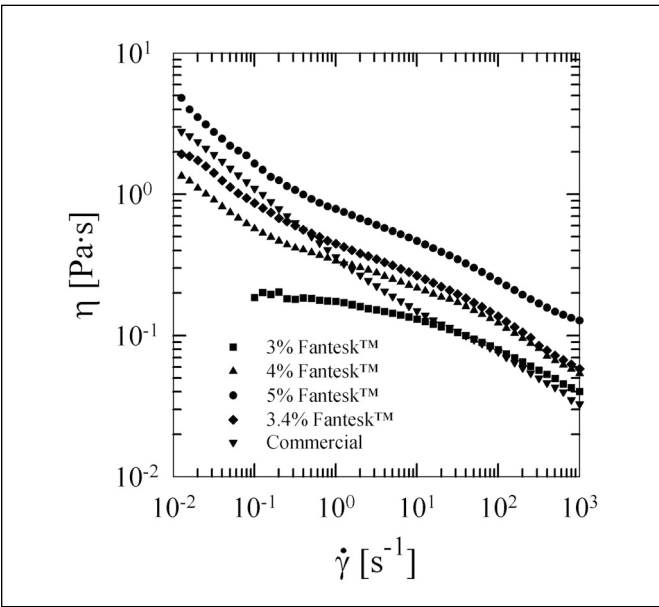


Figure 1—Viscosity of soft-serve mixes at 6 °C

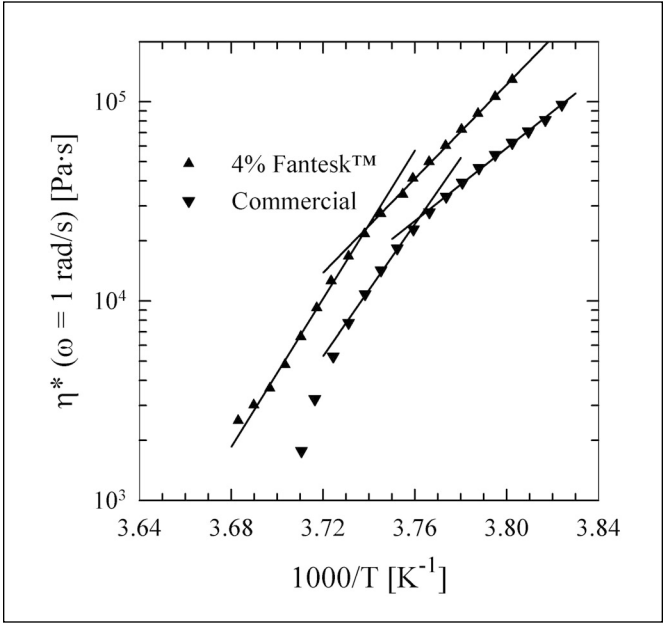


Figure 2—Temperature dependence of the complex viscosity at a frequency of 1 rad/s of the 4% Fantesk™ and commercial soft-serve ice creams. Lines are fits to the data showing the 2 regions of Arrhenius temperature dependence.

perature was increased in 0.5 °C steps. The sample was allowed to equilibrate for 2 min at each temperature before measuring the complex viscosity, which was long enough to reach a constant value. Three distinct regions of behavior are seen on the Arrhenius plot in Figure 2. At low temperatures there is a region of constant slope, followed by a sharp transition to a region of higher slope, indicating a change in the flow mechanism at the transition temperature. Goff and others (1993, 1995) have discussed the importance of the serum phase's freeze concentration in determining the structure of ice cream. They attributed a change in the temperature dependence of the dynamic properties to close packing of ice crystals at a critical temperature, and much lower modulus values were measured above this temperature. Although the ice phase fraction will change throughout the temperature range in Figure 2, the change in slope implies a qualitative change in the mobility of the serum phase such that, at higher temperatures, further melting of ice leads to much greater changes in the complex viscosity than at lower temperatures. Because the exact nature of this change is not known, the intersection of the fits to the data in the 2 temperature regimes is simply called a transition temperature in Table 2. At the highest temperatures, the sample has melted and there is no clear trend. The final melting point is not defined as clearly as the lower transition temperature. The values given in Table 2 are based on the final point that lay on the melting curve, which will necessarily underestimate the true melting point by up to 0.4 °C. The difference between the transition temperature and the melting temperature was nearly constant for all samples at 2.4 to 2.7 °C. Assuming that the ice phase fraction changed from zero at the melting temperature to the same value at the transition temperature, temperatures at the same relative position in this range should have the same ice phase fraction even as the temperature range shifts, depending on the freezing properties of the mix. Since the transition temperature could be determined more precisely, all measurements for each sample were conducted 1.7 °C above the transition temperature, and the draw temperature

was adjusted to be as close to the measurement temperature as possible. The activation energy for the Fantesk™ samples at $T_{\text{transition}} > T > T_{\text{melting}}$ was 430 ± 90 kJ/mol, whereas for the commercial soft-serve it was 340 ± 60 kJ/mol. This corresponds to a change of up to 100% in the complex viscosity for a 1 °C change in temperature, indicating that the ice fraction has a dramatic effect on the properties of the ice cream. The ratio $\tan \delta G''/G'$ increased about 10% as the temperature was decreased below $T_{\text{transition}}$, and then dropped sharply as the sample melted.

The linear viscoelastic response of the products can be obtained by measuring the storage modulus G' and the loss modulus G'' in small amplitude oscillatory shear flow over a range of frequencies. Figure 3a and 3b show G' and G'' for all of the soft-serves studied. The range of strains for which a linear viscoelastic response was observed depended strongly on frequency. The strain used for the measurements in Figure 3 varied from 0.01% at high frequency to 0.3% at low frequency. The results show that there was little effect of variations in the Fantesk™ formulations, and that the Fantesk™ samples had greater elasticity than the commercial product. The 3.4% and 4% Fantesk™ samples were nearly identical at all frequencies. These samples contained the same amount of starch, but the 3.4% Fantesk™ sample had about half as much fat. At low frequency, G' for these samples was more than twice as high as G' for the commercial sample, while at the highest frequencies the difference was only about 30%. Likewise, G'' was about 70% higher for the Fantesk™ samples at low frequencies, but all of the samples were within 10% of each other at high frequencies. Dynamic property measurements at low frequencies measure the effects of longer relaxation times in the sample. Although the contribution of each phase to the overall viscoelastic response is unknown, the fact that the overrun is similar for each sample, and that the temperature dependence implies that each sample has the same ice phase fraction, the differences in Figure 3 may be due to the contribution of the serum phase. As the serum phase is freeze-concentrated, the relaxation time of the high

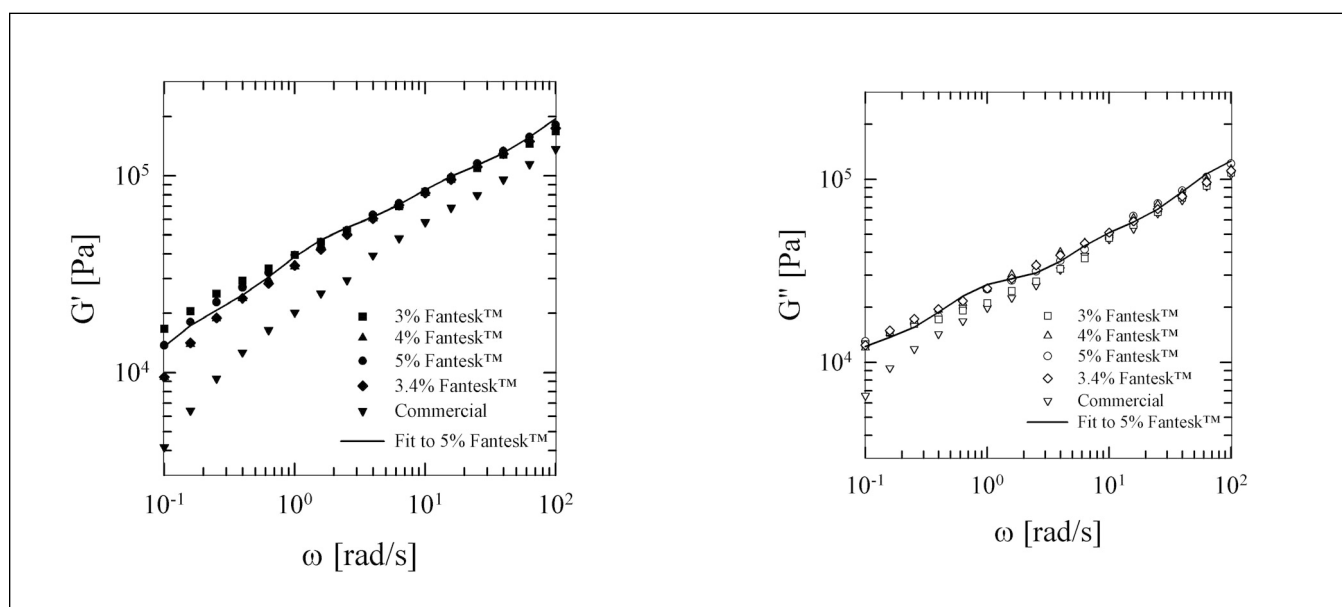


Figure 3—The storage and loss moduli for the soft-serve ice creams. The curves are the predictions of a 6-mode Maxwell model of the properties of the 5% Fantesk sample.

molecular-weight starch will become more important. This could explain why the 5% Fantesk™ has a higher storage modulus than the 3.4% and 4% Fantesk™ samples at low frequency. However, G' for the 3% Fantesk™ sample is higher still. If the starch in the serum phase accounts for differences in G' at low frequency, the lower measurement temperature for the 3% Fantesk™ sample would be expected to have a longer relaxation time and therefore a higher storage modulus, although this effect cannot be quantified. A more important point in Figure 3 illustrates that the properties of the 3% Fantesk™ are within 10% of the other samples at most frequencies, despite the 0.7 °C difference in measurement temperature. Based on the activation energies given above, a temperature change of 0.7 °C should lead to a difference of 65%. The fact that all of the Fantesk™ samples agree so closely justifies the method of determining the measurement temperature in Figure 2, and further shows that the ice phase fraction is the major influence on the rheology of soft-serve ice cream.

Although measurements of the linear viscoelastic properties of ice cream have proven useful, the processing and consumption of ice cream involve strains well outside the linear region. A complete rheological characterization of ice cream therefore also requires measurements of its response to non-linear deformations. A typical measurement at high strains is the viscosity, but the viscosities of the frozen products could not be measured due to slip of the sample in the rheometer. Instead, a series of stress relaxation experiments was performed over a range of strains that extended beyond the linear region. A strain between 0.5% and 100% was instantaneously applied to the sample, and the stress relaxation modulus, G , was measured as a function of time. The results for the 5% Fantesk™ ice cream are shown in Figure 4. As the strain is increased, the stress relaxation modulus decreases, although its time dependence remains the same at all strains. The downward shift of the stress relaxation modulus with increasing strain can be used to define a damping function, $h(\gamma)$. The damping function is defined as the ratio of the stress re-

laxation modulus at a given strain to the value at strains in the linear region. The damping function for these materials can be described by a double exponential function:

$$h(\gamma) = K \exp(-a_1 \gamma) + (1-K) \exp(-a_2 \gamma) \quad (1)$$

The values of K , a_1 , and a_2 for each sample are given in Table 3. The shape of the damping function is similar for all samples for strains up to 10%, but as indicated by the lower value of K (that is, higher $1-K$), $h(\gamma)$ is larger for the 3% Fantesk and commercial ice creams at intermediate strains. Because $h(g)$ is normalized to the low-strain values for each sample, the values in Table 3 only indicate the qualitative differences between samples, not absolute differences in the stress relaxation modulus at a given strain.

The samples can be further characterized by a linear viscoelastic spectrum $\{G_i, \lambda_i\}$, which can be obtained for each sample by fitting a multimode Maxwell model to the results of the frequency sweeps:

$$G'(\omega) = \sum_i \frac{G_i \lambda_i^2 \omega^2}{1 + (\lambda_i \omega)^2} \quad (2)$$

$$G''(\omega) = \sum_i \frac{G_i \lambda_i \omega}{1 + (\lambda_i \omega)^2} \quad (3)$$

or the stress relaxation modulus at low strains:

$$G(t) = \sum_i G_i \exp(-t / \lambda_i) \quad (4)$$

The same set of $\{G_i, \lambda_i\}$ should fit the results of each experiment, so a fit was obtained to minimize the total error, with equal weight given to the frequency sweep and stress relaxation experiments. This combined fit extends the range of time constants that can be determined, since the frequency

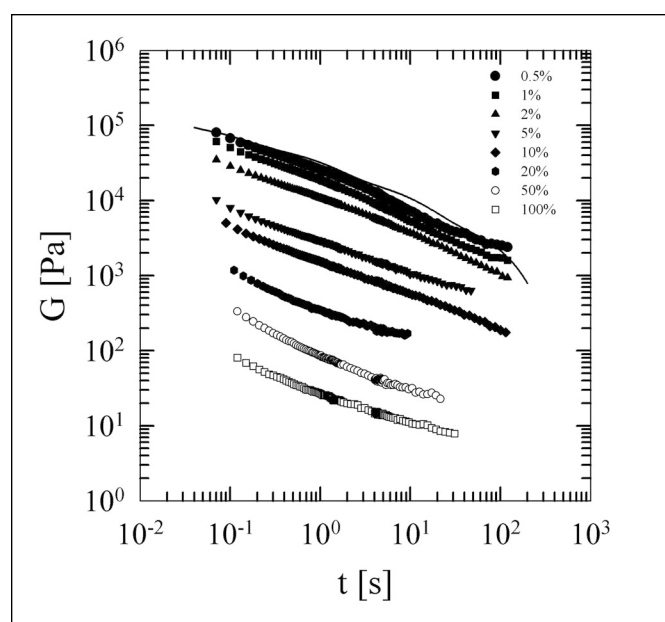


Figure 4—The stress relaxation modulus at various strain levels for the 5% Fantesk™ soft-serve ice cream

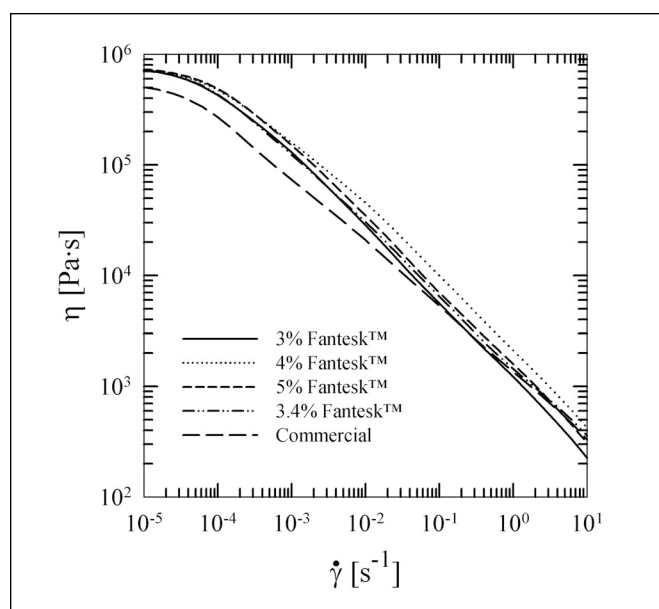


Figure 5—The predictions of the K-BKZ constitutive equation for the viscosity of the soft-serve ice creams

sweep will be characterized by time constants that are the inverse of the frequency range studied ($\lambda = 0.01 - 10$ s), whereas the stress relaxation will be characterized by time constants that depend on the length of the experiment ($\lambda = 0.1 - 100$ s). Six relaxation modes were used for each product. The individual values $\{G_i, \lambda_i\}$ in this case are essentially fitting parameters, and no physical meaning can be assigned to them, other than noting that soft-serve ice cream must be characterized by a broad range of relaxation times. However, the linear viscoelastic spectra can be used to compare different materials by calculating a zero-shear-rate viscosity $\eta_0 = \sum G_i \lambda_i$ and a Maxwell relaxation time $\lambda_0 = \sum G_i \lambda_i^2 / \sum G_i \lambda_i$. These results are summarized in Table 4. As expected from Figure 3, the values for all of the Fantesk™ products are similar, and the commercial product has a lower viscosity. The longer relaxation time for the commercial product is a result of a slower decay of its stress relaxation modulus. The fit for the 5% Fantesk™ is shown in Figure 3 and 4. Note that extrapolating the predictions of Eq. 3 beyond 100 s predicts a sharp decline, whereas the data do not indicate any change in behavior. The maximum measurement time in Figure 4 is limited by the sensitivity of the rheometer, and if the data continued the same trend at longer times, higher values of h_0 and l_0 would be predicted. The values in Table 3 must therefore be viewed as lower bounds on h_0 and λ_0 , rather than true zero-shear-rate values.

Even though the true η_0 and λ_0 values are higher, the values in Table 4 are still much higher than would be expected based on the consumption of soft-serve ice cream. The sensitivity of the ice cream's structure to deformation can be seen in Figure 4, where the stress relaxation modulus drops sharply with increasing strain. Based on the linear viscoelastic spectrum and the damping function obtained above, it is possible to estimate the viscosity and relaxation time at more typical shear rates by using the K-BKZ constitutive equation:

$$\tau(t) = \int_{-\infty}^{t'} m(t-t') h(\gamma) \mathbf{B}(t, t') \dot{\epsilon} \quad (5)$$

where $\tau(t)$ is the stress tensor, $m(t-t')$ is the memory function,

$$m(t-t') = \sum_i \frac{G_i}{\lambda_i} \exp[-(t-t')/\lambda_i] \quad (6)$$

$h(\gamma)$ is the damping function, and $\mathbf{B}(t, t')$ is the Finger strain tensor, which describes the deformation applied to the sample. The K-BKZ model is an empirical model that does not explicitly account for the complex structure of the ice cream, although the memory function and damping function will obviously depend on the fluid being studied. The model only assumes that the effects of time and strain are separable: this assumption is justified by the fact that the curves for the stress relaxation modulus in Figure 4 remain nearly parallel for all strains. Equation 5 can then be used to predict the viscosity as a function of shear rate, as shown in Figure 5. Because the predictions of the K-BKZ model could not be validated for soft-serve ice cream in other nonlinear flows, the quantitative accuracy of the results of Figure 6 cannot be determined. However, an important feature of the results is that, despite the different formulations, all products have similar shear-rate dependence at high shear rates, and the viscosity is predicted to drop by over 2 orders of magnitude at a shear rate of 1 s^{-1} . A shear rate-dependent relaxation

time can also be defined as

$$\lambda(\dot{\gamma}) = \frac{\Psi_1(\dot{\gamma})}{2\eta(\dot{\gamma})} \quad (7)$$

where $\Psi_1(\dot{\gamma})$ is the first normal stress coefficient. As shown in Table 4, the relaxation time at 1 s^{-1} is over 3 orders of magnitude smaller than predicted by linear viscoelastic measurements. For the form of the damping function used in Eq. 1, the K-BKZ model predicts aphysically large decreases in the viscosity at high shear rates (Larson and Monroe 1984), so the viscosity cannot be predicted at shear rates higher than 10 s^{-1} in this case.

Conclusions

A COMPLETE RHEOLOGICAL CHARACTERIZATION WAS OBTAINED for a commercial soft-serve ice cream, and for 4 different ice creams made with a starch-lipid fat replacer. When differences in the freezing behavior were taken into account, only minor changes were observed between Fantesk™-based ice creams with different fat and starch levels. All of the Fantesk™-based ice creams were more elastic than the commercial product in small amplitude oscillatory shear flow. Stress relaxation experiments combined with the results of linear viscoelasticity measurements allowed the viscosity in shear flow to be calculated. These predictions showed that the viscosities of all formulations are expected to have similar shear-rate dependence. Measurements of mix properties, overrun, and melting behavior also showed that the Fantesk™-based ice creams were similar to the commercial product.

References

- Adapa S, Dingeldein H, Schmidt KA, Herald TJ. 2000. Rheological properties of ice cream mixes and frozen ice creams containing fat and fat replacers. *J Dairy Sci* 83:2224-2229.
- Brandt LA. 2000. Novel ingredients for lowfat foods. *Prep Foods* (Oct 2000):49-52.
- Dea ICM, Richardson RK, Ross-Murphy SB. 1984. Characterization of rheological changes during the processing of food materials. In: Phillips GO, Wedlock DJ, Williams PA, editors. *Gums and stabilizers for the food industry*. Vol. 2. Oxford: Pergamon Press. P 357-366.
- Fanta GF, Eskins K. 1995. Stable starch-lipid compositions prepared by steam jet cooking. *Carbohydr Polym* 28:171-175.
- Fanta GF, Eskins K, inventors; Agricultural Research Service, United States Department of Agriculture, assignee. March 16, 1999. Non-separable compositions of starch and water-immiscible organic materials. U.S. patent 5,882,713.
- Goff HD, Caldwell KB, Stanley DW, Maurice TJ. 1993. The influence of polysaccharides on the glass transition in frozen sucrose solutions and ice cream. *J Dairy Sci* 76:1268-1277.
- Goff HD, Freslon B, Sahagian ME, Hauber TD, Stone AP, Stanley DW. 1995. Structural development in ice cream - dynamic rheological measurements. *J Texture Stud* 26:517-536.
- Goyal GK, Srinivasan MR. 1973. The quality of soft-serve ice cream as influenced by the levels of fat, emulsifier, sucrose substitutes, and processing conditions. *J Food Sci Technol* 10:122-124.
- Larson RG, Monroe K. 1984. The BKZ as an alternative to the Wagner model for fitting shear and elongational flow data of an LDPE melt. *Rheol Acta* 23:10-13.
- Millard MM, Dintzis FR, Willett JL, Klavons JA. 1997. Light-scattering molecular weights and intrinsic viscosities of processed waxy maize starches in 90% dimethyl sulfoxide and H_2O . *Cereal Chem* 74(5):687-691.
- Shama F, Sherman P. 1966. The texture of ice cream: 2. Rheological properties of frozen ice cream. *J Food Sci* 31:699-706.
- Sherman P. 1965. The texture of ice cream. *J Food Sci* 30:201-211.
- Sherman P. 1966. The texture of ice cream: 3. Rheological properties of mix and melted ice cream. *J Food Sci* 31:707-716.
- MS 20010127 Submitted 3/11/01, Accepted 7/9/01, Received 7/17/01

The technical assistance of Steven A. Lyle and A.J. Thomas is gratefully acknowledged. This work was financially supported by the United States Department of Agriculture. Names are necessary to report factually on available data; however, the USDA neither guarantees nor warrants the standard of the product, and the use of the name by the USDA implies no approval of the product to the exclusion of others that may also be suitable.

Author Byars is affiliated with the National Center for Agricultural Utilization Research, 1815 N. University Street, Peoria, IL 61604. Direct inquiries to author at Byars (E-mail: byarsja@ncaur.usda.gov).